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Past and Present-day Ice Mass Variation on Svalbard Revealed by Superconducting Gravimeter, GPS and VLBI Measurements

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Abstract

The measured uplift in Ny-Ålesund has varied with geodetic technique, analyzed strategy, and the time period used. This has caused problems for both reference frame issues as well as the geophysical interpretations of the results. In Arctic areas deglaciation after the last glacial maximum, Holocene ice mass variation, and present day ice melt contribute to the land uplift. In addition, tectonic contributions cannot be excluded. We use both geometric and gravity data from the observatory in Ny-Ålesund as well as in-situ mass balance measurements of local glaciers to separate the different processes contributing to the land uplift in Ny-Ålesund and Svalbard. Measurements from the geodetic observatory in Ny-Ålesund indicate land uplift much larger than expected from traditional models of glacial isostatic adjustment. In addition, the land uplift shows large variations from year to year. A combination of the measured variations in the land uplift along with local ice mass variations give a good constraint on the land uplift caused by the present day ice melt. However, we are still not able to explain all the measured uplift. The changes in measured gravity are consistent with the geometric measurements but also much larger than expected from the glacial isostatic adjustment and the present day ice melt. The ratio of unexplained gravity change and unexplained geometric uplift indicate a viscoelastic process. The unexplained uplift is most likely caused by late Holocene ice mass variations.

1. Introduction

Earlier studies of the uplift in Ny-Ålesund have demonstrated large discrepancies. The differences are found between different techniques, analysis strategies, time periods, and observations and models [1, 5, 6, 9, 12]. In ITRF2005 [1], different velocities for the different techniques were given. The GPS receivers for different velocities before and after 2003 were included. The reason for this change in velocity was unknown and caused large problems for reference frame realizations. In Figure 1, the uplift given in ITRF2005 and ITRF2008 [2] for the two GPS receivers, NYAL and NYA1, and the VLBI antenna are plotted. The velocity change was introduced in 2003 for the GPS receivers to give a difference in height of above six centimeters if extrapolated to 2012.

In [6] and [9] the elastic response on the present day ice melt (PDIM) was proven to explain the time varying component of the uplift. The measured uplift has also been larger than expected from the viscoelastic response on the last glacial period [10]. [12] argued that a very large present day ice melt could explain the large uplift; however, recent mass balance measurements, e.g. [7, 8], do not indicate a large ice melt. Using both gravity and geometric measurements, [9] argues that the large uplift is most likely due to the deglaciation after the little ice age which ended around 1890 in Ny-Ålesund.

In this paper we summarize the most important findings in [6] and [9]. We discuss these findings in relation to reference frame issues.

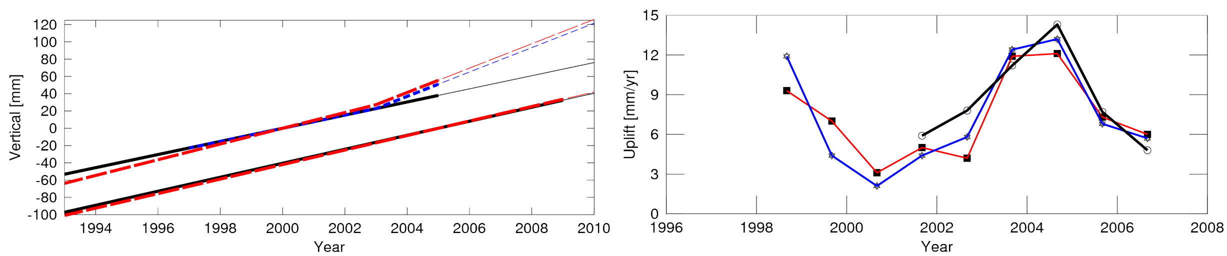

Figure 1. Height in Ny-Ålesund from ITRF solutions (left) and measured and modeled yearly uplift (right). Left panel: The three upper curves are from ITRF2005, and the two lower curves are from ITRF2008. Solid (black) lines are VLBI, and stippled (red and blue) lines are GPS (NYAL and NYA1, respectively). The thin lines indicate extrapolations in the period after the actual reference realizations were performed. Right panel: Stars (blue) are modeled, boxes (red) are from GPS, and circles (black) are from VLBI.

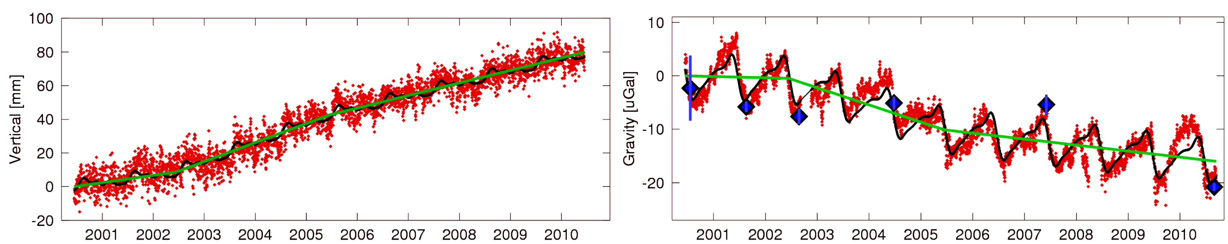

Figure 2. Time-series for uplift (left) and gravity (right) in Ny-Ålesund. The small red dots are daily vertical GPS (left) and SCG (right) measurements. Large blue diamonds are absolute gravity measurements.

2. Measurements and Results

The GPS data from Ny-Ålesund are analyzed using the GIPSY-OASIS II software packages in precise point position mode, and the VLBI data is analyzed using CALC/SOLVE. The superconducting gravimeter (SCG) data are filtered to daily values and calibrated using absolute gravity observations. For more details about the processing see [5] and [9]. Daily coordinate time-series are plotted in Figure 2 while the uplift rates for the periods 2000 to 2003, 2003 to 2006, and 2006 to 2010 are included in Table 1. We see a similar long term pattern for the GPS and SCG measurements, indicating that geometric and gravimetric techniques observe the same geophysical phenomena. However, the annual fluctuations are much larger with SCG. This is probably due to seasonal variations in hydrological conditions. Yearly variations in the ice and snow cover may greatly contribute.

In [5] and [6], large and systematical differences between uplift rates based on GIPSY on the one hand and GAMIT and VLBI on the other side were revealed. The GPS solutions given in [9] were based on GIPSY but differ significantly from the GIPSY solutions in [5] and [6]. The main difference in the analysis strategy is that the absolute phase center calibration [4] had replaced the old relative antenna phase center calibration. This newer GIPSY solution was in accordance with the GAMIT and VLBI solutions in [5] and [6].

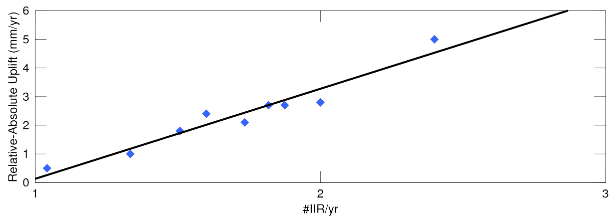

Figure 3. Differences in uplift as a function of the number of new Block IIR satellites. The line is the regression line of the differences.

The uplift based on GIPSY with relative versus absolute phase center calibration differs. The differences vary for different time periods. In Figure 3, these differences are plotted as functions of the number of block IIR satellites launched each year in the same time period. Note the high correlation of 0.93 between the differences in measured uplift and the number of new block IIR satellites. The use of relative versus absolute antenna phase center calibration may cause systematic effects on the estimated positions and time-series [4]. At high latitudes where we have no satellites near zenith, this may contribute especially to different uplift rates. The results presented in Figure 3 indicate that the main problem is the relative calibration of the Block IIR satellite antenna phase center.

Table 1. Measured and modeled values of piecewise linear trends for gravity and uplift.

Period	$\dot{h}_{meas}(mm/yr)$	$\dot{g}_{meas}(\frac{\mu Gal}{yr})$	$\dot{h}_{gia}(mm/yr)$	$\dot{g}_{gia}(\frac{\mu Gal}{yr})$	$\dot{h}_{pdim}(mm/yr)$	$\dot{g}_{pdim}(\frac{\mu Gal}{yr})$
2000–2002	4.4±0.27	-0.23±0.12	1.6	-0.24	0.7	-0.18
2002–2005	11.3±0.36	-3.22±0.13	1.6	-0.24	6.4	-1.67
2005–2010	7.4±0.19	-1.10±0.07	1.6	-0.24	2.1	-0.54
2000–2010	8.5±0.04	-1.77±0.01	1.6	-0.24	3.1	-0.81

3. Geophysical Models

In [5] the uplift in Ny-Ålesund due to PDIM was estimated to be 3.2 mm/yr for the period between 1993-2008. They used a detailed ice and mass balance model for Svalbard which takes the spatial pattern of present day ice mass loss into account as forcing for the elastic uplift modeling. The elastic uplift modeling followed the approach in [3]. The ice and mass balance model correspond to a mean ice mass loss of 0.37 m water equivalent (mweq)/yr across Svalbard. The ratio between uplift and PDIM change was reported to be 8.7 mm/mweq. This implicitly assumes the pattern of ice mass changes to be proportional for all time spans. In [6] the modeled uplift rates were estimated by multiplying the reported ratio of 8.7 mm/mweq with mass balance values of nearby glaciers obtained by the Norwegian Polar Institute [7]. The results are plotted in Figure 1 together with yearly measured uplift. The yearly measured uplift is obtained by fitting a step function (a constant function extended with a heavy side function for each year, see [6] for details) to a mean of the time-series from GPS and VLBI in Ny-Ålesund. Note the accordance between measurements and observations (correlation coefficient of 0.8).

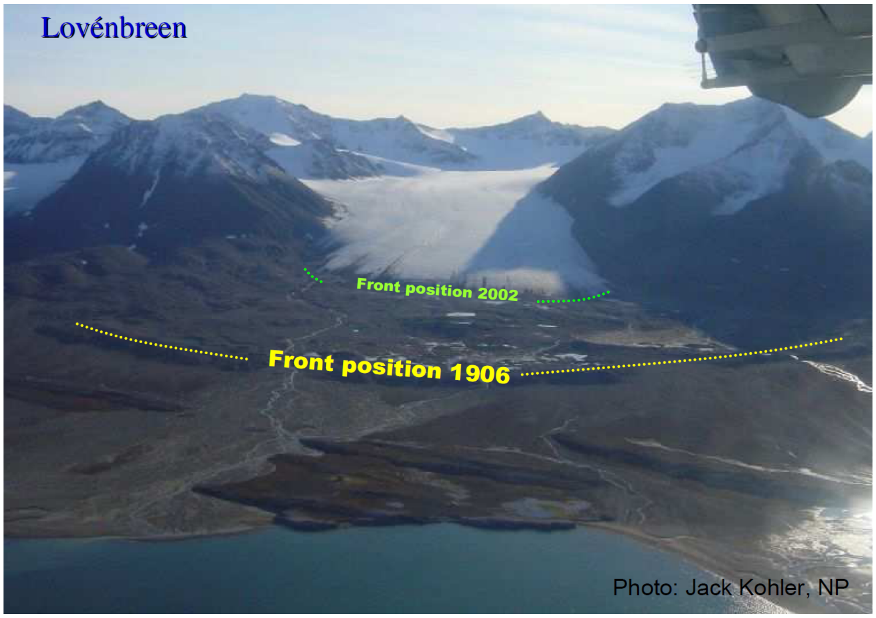

Figure 4. Lovénbreen. The figure illustrates the retreat of Lovénbreen close to Ny-Ålesund.

For the time span from 16 June 2000 to 15 June 2010 we predicted an uplift of 3.1 mm/yr due to PDIM. In [6] the uplift due to GIA was reported to be 1.6 mm/yr. The modeled uplift due to these processes is then 4.7 mm/yr. That is 3.8 mm/yr smaller than actually measured. Using the theory developed in [13], we obtained a ratio between gravity change and an uplift of -0.15 μGal/mm for a viscoelastic process like GIA, while the ratio is approximately -0.26 μGal/mm if the uplift is an elastic response to the PDIM. Using these ratios [9] find that the gravity change corresponding to the modeled uplift (from GIA and PDIM) is -1.05 μGal/yr. Therefore, we have an unexplained uplift of 3.8 mm/yr and an unexplained gravity change of -0.72 μGal/yr. The ratio between the unexplained gravity change and the unexplained uplift is -0.19 μGal/mm, indicating a viscoelastic process. This is most likely a viscoelastic response to the retreat of the glacier in the vicinity of Ny-Ålesund after the little ice age [9] (see Figure 4 for an illustration).

4. Conclusion

Detailed analysis of the VLBI, GPS, and SCG measurements at Ny-Ålesund and Svalbard, revealed variations in uplift and gravity. The modeled uplift and gravity change, based on in-situ PDIM measurements given in Table 1, is consistent with measured values. Also, variations in uplift from year to year are consistent with measured ice-mass loss. An increase in ice-mass loss rate is present until 2005, while there is a decrease after 2005. This demonstrates that geodetic techniques are able to recapture changes in PDIM.

Geophysical GIA and PDIM models under-predict the observed uplift. The large uplift is possibly due to the retreat of the glacier in the vicinity of Ny-Ålesund after the little ice age.

The presence of non-linear features in the geodetic time-series from Ny-Ålesund make it necessary to use consistent time periods when making geophysical interpretations. Time-series from different time spans will contain different geophysical signals and are consequently not comparable.

Non-linear station motion is also a huge challenge for accurate reference frame realization (e.g., the ITRF2005 effect showed in Figure 1). The present regime with reference frames given as a catalog of coordinates and velocities has proved to be successful. The main problem has been stations in active tectonic areas, which have been excluded from the datum realizations. With the GGOS [11] requirement of a reference frame accuracy of 0.1 mm/yr, many more stations will appear unstable. In this paper we have studied the significant contribution from ice on the uplift. Loading effects due to hydrology, atmosphere, etc. may also have significant impact. In addition, tectonic and neo-tectonic effects are important. To achieve an accuracy of 0.1 mm/yr, methods to incorporate different kinds of non-linear effects into the reference frame have to be developed. The authors see two different solutions: (1) either a more dynamic realization of the reference frame, for instance a daily, weekly, or monthly reference frame realization allowing the network stations to move non-linearly, or (2) a station motion model including more geophysical effects.

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